

Antibaryonic dark matter

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Assuming existence of (very) heavy fourth generation of quarks and antiquarks we argue that antibaryon composed of the three heavy antiquarks can be light, stable and invisible, hence a good candidate for the Dark matter particle. Such opportunity allows to keep the baryon number conservation for the generation of the visible baryon asymmetry. The dark matter particles traveling through the ordinary matter will annihilate with nucleons inducing proton(neutron)-decay-like events with ~ 5 GeV energy release in outcoming particles.

PACS numbers: 95.35.+d, 14.65.Jk, 14.20.Pt

I. INTRODUCTION

One of Sakharov's condition of existence of the Universe as we know it, is baryon number violation [1]. It seems indisputable from the observation of the baryonic matter over antimatter dominance, if the Universe got nonzero baryon charge at early evolution stage. However, if the Dark matter of the Universe (DM) is antibaryonic, and consisting of exactly the same number of antiquarks as usual matter does, this Sakharov's requirement is no more obligatory. Such opportunity can be only justified if DM antibaryons satisfy the following conditions: they are stable (at least at the Universe lifetime scale) and neutral; their annihilation with normal matter is an extremely rare phenomenon; moreover, negative results of direct searches for Dark matter place upper limits on cross section of DM elastic scattering off baryons.

In this Letter we consider a minor modification of the Standard Model (SM) where DM can be formed by antibaryons. Namely, we examine the SM with 4 generations of quarks (SM4) [11], which was widely discussed in literature, and argue that baryons built from the heaviest quark generation (t' and b') can be light, stable and invisible.

With baryon number conserved, there should be a parity of "Light" baryons and "Dark" antibaryons in the Universe. We thus conclude from measurement of DM mass density in the Universe (about 5 times higher than baryonic mass density [4]) that "Dark" antibaryons should have mass of about 5 GeV. One and the same mechanism — antibaryon formation — is responsible for both DM and baryon asymmetry generations in the early Universe. It is worth noting that since in the model the baryon number enters both matter components (baryonic and dark), it naturally explains the coincidence (within one order of magnitude) of visible and dark matter contributions to the present density of the Universe.

The idea of baryon-symmetric Universe [2] was extensively studied in literature, and several mechanism to generate antibaryonic dark matter have been suggested, for a recent review see [3]. In our model a specific production mechanism does the job, and the phenomenology is different except the main signature of all antibaryonic dark matter models: an induced nucleon decay.

II. LIGHT BARYONS BUILT OF HEAVY QUARKS

Light u and d quarks in the normal baryons (protons and neutrons) are bound by the strong interaction. For baryons consisting heavy t' and b' quarks the extra huge binding energy arises due to the scalar exchange between each pair of quarks. Indeed, scalar fields provide attractive forces between fermions with the strength proportional to the product of Yukawa couplings, *i.e.* increasing with the fermion masses.

The naive (perturbative) estimates of the binding energy of two heavy quarks Q due to light scalar exchange is

$$E_{\text{binding}} \sim \frac{m_Q}{2} \left(\frac{Y_Q^2}{4\pi} \right)^2, \quad (1)$$

where m_Q is quark mass, Y_Q is its Yukawa coupling to the light scalar (like in the SM, the SM4 quark masses are proportional to the Yukawa constants, $m_Q \propto Y_Q$). The bound state of heavy quarks will be much lighter than the sum of quark masses because of large negative value of this binding energy, that can be even of the order of the sum of the quark masses: *e.g.* a meson-like *light* bound state of 6 t -quarks and 6 t -antiquarks was considered in Ref. [5].

A more economic configuration of heavy quarks bound by strong scalar exchange is a bubble of the false vacuum $\phi = 0$, surrounded by domain wall, inside which massless fourth generation quarks are confined. Indeed, in this case instead of quark masses the energy of the false vacuum bubble contributes to the configuration mass. The later may be much smaller than the sum of the quark masses if the radius of the bubble is small.[12] Below we describe a toy model where such a configuration might be realized.

III. TOY MODEL

We assume factorization of quark fields and the domain wall between true and false vacua by localizing quarks inside a sphere of radius R , where the coupled to quarks scalar ϕ (Higgs field) is fixed to zero. We thus estimate the energy of the whole system as a sum of two noninteracting parts: quarks and domain wall. Because of this factorization, such toy model overestimates the total energy but is sufficient for our purposes to illustrate the main idea we put forward.

The simple spherically symmetric bubble profile for the scalar field static configuration ($\phi = f(r)$) is schematically shown in Fig. 1 a) for $R = 0.1 \text{ TeV}^{-1}$ as an example. It is obtained numerically by minimizing the classical energy of

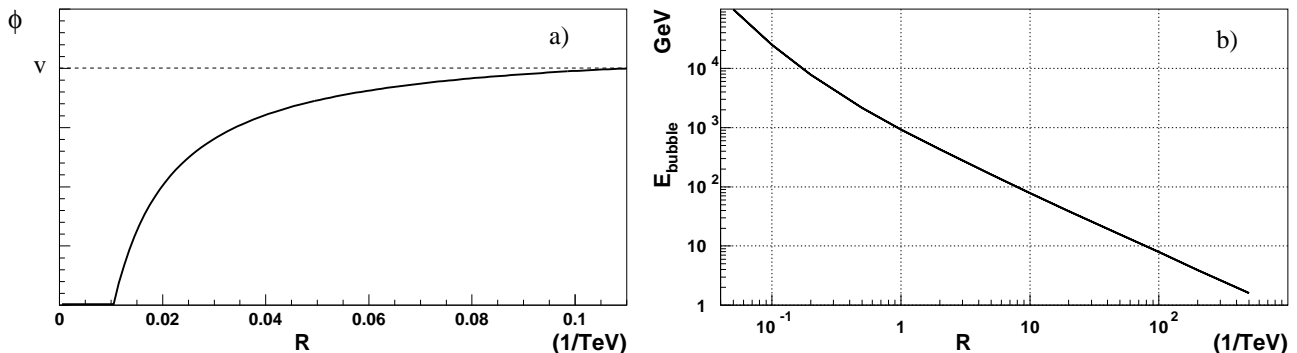


FIG. 1: a) The scalar field R -dependence for inner radius fixed at $1/10 \text{ TeV}^{-1}$; b) Bubble energy dependence on inner radius.

the scalar bubble, that includes the potential energy of false vacuum inside the sphere, and both the potential and gradient energy in the region of domain wall between false and true vacua:

$$E^{\text{bubble}} = \frac{4}{3}\pi R^3 v^2 + \int_R^\infty \left(\frac{\lambda}{2}(f^2 - v^2)^2 + \left(\frac{df}{dr}\right)^2 \right) 4\pi r^2 dr. \quad (2)$$

For bubble radius R smaller than inversed vacuum expectation value of the SM Higgs field $v = 246 \text{ GeV}$, $R < 1/v$, the main contribution to the energy comes from the domain wall rather than internal volume (false vacuum energy). The optimal “thickness” of the domain wall is roughly proportional to R , thus the total energy for small radius turns out to be also proportional to the bubble radius (see Fig. 1, b) as

$$E^{\text{bubble}} \approx 4.2\pi v^2 R. \quad (3)$$

Inside the bubble quarks are massless, therefore only kinetic energy $E_{\text{kinetic}}^{\text{quark}} \sim 1/R$ and potential energies due to Yukawa and strong interactions contribute to total mass of quark configuration in the bubble,

$$E^{\text{quarks}} \sim \left(3 - 2 \frac{Y^2}{4\pi} - 3\alpha_s \right) \frac{1}{R}. \quad (4)$$

Here the first term in parenthesis is the kinetic energy of three quarks inside the bubble, the second term comes from two pairs of Yukawa interactions (between left and right quarks only, see below) and the third term accounts for strong coupling in all three pairs. For the moment, we ignore the contribution of $U(1)_Y$ and $SU(2)_W$ gauge interactions, that can be both negative and positive depending on the particular quark composition.

If the quark contribution 4 to the total energy were negative, which requires large values of Yukawa couplings $Y \gtrsim 4$ (not far from region where perturbative unitarity is lost, $Y^2/(4\pi^2) \gtrsim 1$), the bubble is squeezed to a tiny size by

both domain wall pressure and scalar exchange interaction. The infinite grip of the bubble may be prevented by the running (decreasing) of Yukawa couplings with energy scale: Yukawas are smaller at smaller radius. Then the bubble is stabilized at some R , when

$$2 \frac{Y^2(R)}{4\pi} + 3 \alpha_s(R) \approx 3. \quad (5)$$

In this case the quarks contribution to the total energy is canceled by equality of the potential and kinetic terms, and the baryon mass is kept to be $\sim E^{\text{bubble}}(R)$.

If reliable SM4 renormalization group calculations would exist in case of large Yukawas, one could calculate the stabilization radius R_* by solving

$$\begin{aligned} \frac{d}{dR} (E^{\text{quarks}} + E^{\text{bubble}}) |_{R=R_*} &= 0, \\ \frac{d^2}{dR^2} (E^{\text{quarks}} + E^{\text{bubble}}) |_{R=R_*} &> 0. \end{aligned} \quad (6)$$

Introducing β -functions of the gauge and Yukawa couplings as follows

$$\beta_{\alpha_s} = \frac{d\alpha_s}{d\log \mu}, \quad \beta_Y = \frac{d(Y^2/4\pi)}{d\log \mu},$$

and setting energy scale at $\mu = 1/R$ we obtain from eq.6 for the value of R_* :

$$4.2\pi v^2 R_*^2 = 3 - 2 \frac{Y^2}{4\pi} - 3\alpha_s - 2\beta_Y - 3\beta_{\alpha_s}, \quad (7)$$

where in the r.h.s. we omit the explicit dependence on R_* . For the extremum at $R = R_*$ to be minimum one finds from 6

$$4.2\pi v^2 R_*^2 > 2\beta_Y + 3\beta_{\alpha_s} + 2\beta'_Y + 3\beta'_{\alpha_s}, \quad (8)$$

where primes on r.h.s. refer to derivatives with respect to $\log \mu$ evaluated at $\mu = 1/R_*$. If higher order contributions to β -functions are subdominant, condition 8 is fulfilled and the configuration is stable. Thus, at moderate values of coupling constants the simple estimate we use would be enough. However, for $Y \sim 4$ -5 the SM4 renormalization group equations [7] suggest that both one-loop and two-loop contributions are large and of the same order, but of the opposite signs. This demonstrates that no reliable calculations can be done, and even direction of running (falling or growing with energy scale) is unknown. In addition the bare Yukawa constants are not known. Thus, having an idea to explain DM by new antibaryons, we suppose that t' and b' Yukawa couplings decrease with energy and stabilization 5 is reached at $1/R \sim 100$ TeV, hence the antibaryon mass is near 5 GeV, as needed. This requires the masses of 4-th generation to be $m_Q \gtrsim 700$ GeV, close to the present sensitivity of the direct searches at LHC [9]. We note, that perturbative calculations of the 4-th generation contribution to electroweak observables [4] and the SM Higgs boson production also become unreliable (see *e.g.* [10]), and one might speculate they are canceled. Otherwise, a new degree of freedom introduced to the model may cure the situation and cancel the perturbative contributions of the 4-th generation.

Although we can not predict the masses of the baryon family members made of the 4-th generation quarks, some important properties can be derived. In particular, the main feature is that the lightest baryons turn out to be neutral and to have vanishing coupling to Z -boson. Otherwise it would contribute to Z -boson width, see Sec.IV.

IV. BARYON FAMILY OF 4-TH GENERATION QUARKS

Inside the false vacuum bubble the broken $SU(2)_W \times U(1)_Y$ symmetry is restored and for the proposed baryon candidates the chirality of quarks matters. Baryons made of only lefthanded or only righthanded quarks have no scalar coupling. We thus consider only combinations of two lefthanded quarks and one righthanded quark, or two righthanded quarks and one lefthanded quark: $q'_L q'_R q'_R$ and $q'_R q'_L q'_L$ ($q'=t'$ or b').

We should take into account corrections to the effective coupling of quarks arising from the weak and hypercharge interactions. They change the stabilization radius and therefore mass of the state. We list all configurations with corresponding energies due to $U(1)_Y$ and $SU(2)_W$ gauge interactions and couplings to photon and Z -boson in Table I. From the LEP data the Z -boson partial width to invisible final state except for three neutrino is below 6×10^{-4} [4],

TABLE I: Baryon configurations with energies due to Yukawa ($\alpha_{t'} \equiv Y_{t'}^2/(4\pi)$, $\alpha_{b'} \equiv Y_{b'}^2/(4\pi)$), $U(1)_Y$ and $SU(2)_W$ gauge interactions and their effective couplings to photons (Q^γ , in units of proton electric charge), and Z -boson via vector and axial currents (g_V^Z and g_A^Z , in units of g_2). Negative binding energy refers to repulsive forces. The DM candidate is anti- $b'_R t'_L b'_L$.

baryon	Yukawa	$U(1)_Y$	$SU(2)_W$	Q^γ	g_V^Z	g_A^Z
$b'_L b'_R b'_R$	$2\alpha_{b'}$	0	0	-1	$-\frac{1}{2} + 2s^2$	$-\frac{1}{2}$
$b'_L t'_R b'_R$	$\alpha_{t'} + \alpha_{b'}$	$\frac{2}{3}\alpha_Y$	0	0	$-\frac{1}{2}$	$-\frac{1}{2}$
$b'_L t'_R t'_R$	$2\alpha_{b'}$	$-\frac{2}{3}\alpha_Y$	0	+1	$-\frac{1}{2} + 2s^2$	$-\frac{1}{2}$
$t'_L b'_R b'_R$	$2\alpha_{b'}$	0	0	0	$\frac{1}{2}$	$\frac{1}{2}$
$t'_L t'_R b'_R$	$\alpha_{t'} + \alpha_{b'}$	$\frac{2}{3}\alpha_Y$	0	+1	$\frac{1}{2} - 2s^2$	$\frac{1}{2}$
$t'_L t'_R t'_R$	$2\alpha_{t'}$	$-\frac{2}{3}\alpha_Y$	0	+2	$\frac{1}{2} - 4s^2$	$\frac{1}{2}$
$b'_R b'_L b'_L$	$2\alpha_{b'}$	$\frac{1}{3}\alpha_Y$	$-\alpha_W$	-1	$-1 + 2s^2$	-1
$b'_R t'_L b'_L$	$2\alpha_{b'}$	$\frac{1}{3}\alpha_Y$	α_W	0	0	0
$b'_R t'_L t'_L$	$2\alpha_{b'}$	$\frac{1}{3}\alpha_Y$	$-\alpha_W$	+1	$1 - 2s^2$	1
$t'_R b'_L b'_L$	$2\alpha_{t'}$	$-\alpha_Y$	$-\alpha_W$	0	-1	-1
$t'_R t'_L b'_L$	$2\alpha_{t'}$	$-\alpha_Y$	α_W	+1	$-2s^2$	0
$t'_R t'_L t'_L$	$2\alpha_{t'}$	$-\alpha_Y$	$-\alpha_W$	+2	$1 - 4s^2$	1

hence “ Z -charge” of the lightest baryon (which is much lighter than half of Z mass, according to our arguments) should be exactly zero. There is only one such a candidate in the Table I: $b'_R t'_L b'_L$ baryon. It is also electrically neutral that is one of the necessary conditions to be DM. Other baryons (if exist) with non-zero coupling to Z should be heavier than $m_Z/2$.

One can expect that most combinations listed in the Table I do not form bound states. Eight out of the twelve listed candidates include a pair of identical quarks. Such pairs should have symmetric spin wavefunction, as two quarks are spatially symmetric, and color antisymmetric; thus their total spin is 1, and there is a spin-spin interaction energy between the remaining third quark and the pair. Strength of the spin-spin interaction is not small in our case of very compact state of relativistic components. Among the four remaining configurations the $b'_R t'_L b'_L$ and $t'_R t'_L b'_L$ have $SU(2)_W$ gauge force *attractive*, hence reducing the bound state masses. The former configuration (our DM) is naturally lighter, as attractive $U(1)_Y$ force also reduces its mass, while repulsive $U(1)_Y$ force increases the mass of charged baryon $t'_R t'_L b'_L$.

We conclude that natural candidate to be DM is $b'_R t'_L b'_L$. Its binding energy is determined mostly by b' quark Yukawa coupling $Y_{b'}$, while the mass of $t'_R t'_L b'_L$ is determined by t' -quark Yukawa $Y_{t'}$. Values of these Yukawas (and hence masses of t' and b') have to be chosen in such a way that cancellation of quark energy 5 for $b'_R t'_L b'_L$ happens at smaller radius R (i.e. at higher energy scale for running couplings) than for $t'_R t'_L b'_L$. Then $t'_R t'_L b'_L$ is much heavier, since the energy of the total configuration is then mostly the bubble energy 3, which grows linearly with R . This consideration suggests that $b'_R t'_L b'_L$ is naturally the lightest of all the baryon configurations listed in Table I, and hereafter we suppose it is existing and its mass is about 5 GeV.

V. DM PRODUCTION AND BARYON ASYMMETRY GENERATION

In the model the baryon asymmetry of the Universe as well as DM component are produced after electroweak phase transition, when the SM Higgs field gains nonzero vacuum expectation value and all quarks and weak bosons become massive. Because of strong Yukawa couplings bound states listed in Table I start to form somewhat earlier. When new phase has conquered the space everywhere except inside the bound states, the latter become massive and decay into lighter bound states and quarks. It is a nonequilibrium process and as a result the required asymmetry between the lightest bound states $b'_R t'_L b'_L$ and $\bar{b}'_R \bar{t}'_L \bar{b}'_L$ may be generated with approximately chosen CP-violating parameters in 4×4 extensions of the CKM matrix. At the same process the rest of baryonic charge transfers to the SM quarks. Then all $b'_R t'_L b'_L$ -baryons annihilate with antibaryonic counterparts leaving a requiring amount of dark matter antibaryons made of $\bar{b}'_R \bar{t}'_L \bar{b}'_L$. Hence, the model under discussion is capable of producing both DM and baryon asymmetry of the Universe.

VI. LIFETIME AND INTERACTIONS OF THE ANTIBARYONIC DM

If even the lightest “Dark” antibaryon has small mass of ~ 5 GeV, it is not stable. Such antibaryons can decay to antiproton, strange or charmed antibaryon via simultaneous transitions of all heavy antiquarks to light antiquarks. Such non diagonal transition can be provided only by weak interactions (a triple W -emission or simultaneous W -exchange and W -emission), but one of the antiquark is righthanded and more complicated diagram is required, like that shown in Fig. 2. It is extremely suppressed by CKM weak couplings to the first (second) generation antiquarks

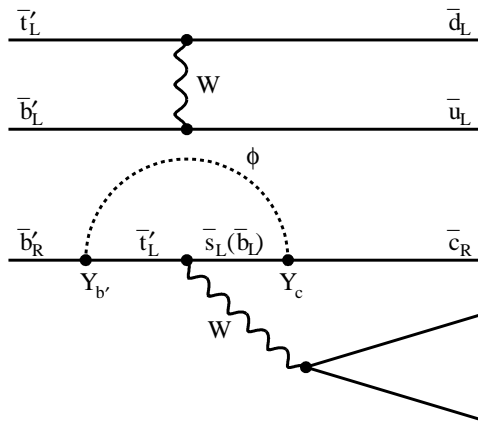


FIG. 2: Diagrams of DM antibaryon decay.

and small Yukawa coupling of the second generation. Thus, 5 GeV antibaryon can (easily) be stable at cosmological time scale.

DM particles scatter off each other with cross sections certainly smaller than the geometric estimate $\sigma \sim 4\pi/R^2$. The number is small enough to satisfy the upper limit from the Bullet cluster 1E 0657-56 [8] and to ensure the stability of dark matter at cosmological time scale in the interesting regions with overdensity: inside galaxies and clusters. Likewise annihilation with baryons is ineffective. However, the latter process is a signature of the antibaryonic DM we propose: annihilation products in cosmic rays may be searched for to test the model.

There are limits on elastic DM scattering off nuclei from direct searches for Galactic DM at (underground) laboratories [4]. Being decoupled from photon and Z -boson, the DM particles scatter off ordinary matter with very small cross section. Also taking into account small energy transfer due to small mass of 5 GeV, one concludes that the standard approach adopted in direct searches for the dark matter particles, with energy release as the main signature, is useless. More promising are experiments on searches for proton decays: though in our model *baryon number is perturbatively conserved*, the annihilation event of dark matter *antibaryon* with proton (neutron) will resemble baryon decay event very closely: only energy release (total energy of the “decay product”) is up to 5 GeV.

VII. CONCLUSION

In this Letter we have argued that DM may be represented by antibaryonic matter, produced by very heavy quarks confined into $M = 5$ GeV bound states, and baryogenesis can be provided without baryon number violation. Neither new (conserved) charges nor interactions are involved. A signature in a Super-K-like detector is proton(neutron)-decay-like event but with more energetic outcoming “decay”-products. Analogous signature anticipated in cosmic rays is annihilation with ordinary matter. A special study is worth to obtain model predictions for cosmic ray experiments and direct searches.

4th generation of SM fermions must be searched for at LHC: expected mass range is 700-900 GeV, close to the present limits [9]. The dynamics we need to construct the light antibaryons from heavy antiquarks may be provided by strong coupling in Yukawa sector, though we have no reliable tools to describe it quantitatively. Hopefully, this can be done using lattice calculations. Note that configurations we operated with are very compact: the antibaryon radius R is much smaller than its naive Compton wavelength $2\pi/M$, but is of order of the constituent masses. One may hope to describe these configurations *in perturbative regime* with new degrees of freedom introduced or by extending the setup with extra spatial dimensions, while effective Yukawa dynamics on the World 3-brane is at strong coupling.

Acknowledgments. The authors are very thankful to A. Mironov, A. Morozov and V. Rubakov for useful discussions. The work of D.G. is supported in part by the grant of the President of the Russian Federation NS-5590.2012.2, by MSE under contract #8412 and by RFBR grants 11-02-01528a, 13-02-01127a.

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 - [11] A modification in lepton sector needed to cancel the SM gauge anomalies is required but its details are irrelevant for our study.
 - [12] The general idea of bound state lighter than constituents is not new: even massless bound states have been discussed in literature [6] but within another setup.